THE BIOFILTRATION OF INDOOR AIR III:
AIR FLUX AND TEMPERATURE AND REMOVAL OF VOCs.

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ABSTRACT

A botanically based biofilter integrated directly into the air handling system of an indoor space removed significant amounts of VOCs present in parts per billion by volume concentrations. For toluene, ethylbenzene and o-xylene, the greatest removal per pass (removal efficiency) was at the slowest influent flux (ca 0.02 m s^{-1}), however the greatest removal per unit time and biofilter volume (elimination capacity) was at the more rapid fluxes (ca 0.1 to 0.2 m s^{-1}). Cooler temperatures allowed greater partitioning of the VOCs into the water column which had a greater impact on removal than its reduction in microbial activity. The halogenated compound PCE, was removed from the air stream but there was little evidence of degradation.

INTRODUCTION

The concentrations of VOCs typically found indoors are very low by industrial biofiltration standards (i.e. typically less than 200 μg m^{-3}) (1, 2). However, since North Americans spend in excess of 85% of their time indoors (3), even these exposure levels are an important public health issue. Traditionally, indoor air quality (IAQ) is maintained through ventilation with new outside air. This practice can greatly increase the energy consumption and operation cost of the building. Our current research is investigating the use of botanically based biofiltration systems as an alterative means of maintaining indoor air quality. The topic of biofiltration of indoor air has been discussed in some detail by Llewellyn (4) and Mallany (5) and their coauthors.

Before this technology can gain acceptance, descriptions of system performance with typical indoor VOCs are required. The monoaromatics, toluene, ethylbenzene and xylene (collectively referred to as TEX) and the chlorinated compound perchlorethylene (PCE) were chosen for this study because of their frequency of occurrence indoors.

The goal of this study was threefold: first, to determine whether the biofilter can remove VOCs present at realistic indoor air concentrations; second, to determine the biofilter's optimum operating conditions in terms of temperature and influent flux for the removal of these VOCs; and third, to determine the relative roles of VOC partitioning into the water column and microbial activity on removal.

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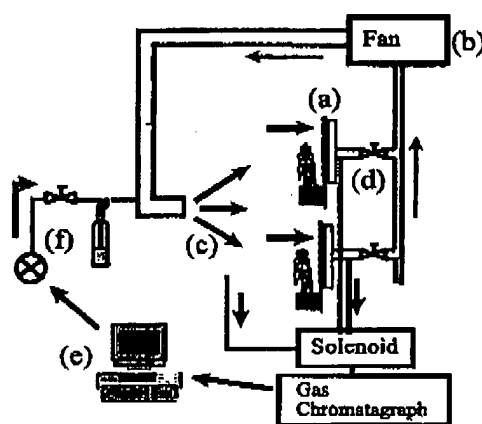
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EXPERIMENTAL METHODS

The Biofiltration System. The test biofiltration system was located on the ground floor of the Canada Life Assurance building (Toronto, Ontario, Canada) as described in detail elsewhere (6-8). The biofiltration system was composed of three components: an array of bioscrubbers through which air was drawn, a region of hydroponic plants and an aquarium (Figure 1). The bioscrubbers (designed by Genetron Systems Inc., Toronto, Ont. Canada) were four air plenums (1.2 x 2 x 0.2 m) separated by 0.7 m with the external rock vertical face of the modules covered with between 1.5 and 2.5 cm of moss (*Plagiomnium cuspidatum* and *Taxiphyllum deplanatum*) on a supporting geotextile cloth. It is reasonable to assume that the moss had superficial surface areas similar to peat, reported as 1.6 m^2 g^{-1} (9).

The biofilters were integrated into the room's air handling system. Air was drawn through a 0.27 m^2 subsection of each bioscrubber by a variable speed centrifugal fan and then circulated back to the room. The flux of the air stream through each individual bioscrubber was varied daily (0.025, 0.05, 0.100 and 0.200 m s^{-1}). At the base of the bioscrubbers was a 3.5 m^3 aquarium containing a variety of plants that circulated water through the hydroponics and down the bioscrubbers. The temperature of the system was set to 20, 25 and 30° C by altering the temperature of the aquarium. The same temperature was applied to all bioscrubbers at the same time. The actual bioscrubber temperature was measured as the effluent air temperature. After changes in temperature, the system was given 7 days to stabilize. The pH was 6.7 ± 0.1 and salinity did not exceed 0.1 mS cm^{-1}.

Analytical Methods. VOC concentrations of the influent and the effluent from each of the 4 bioscrubbers were automatically monitored with an SRI 310 gas chromatograph. To control influent, the chromatograph was interfaced with a peripheral VOC emission system (see Figure 1). The diurnal profile for each VOC started at 0 parts per billion by volume (ppbv) at 18:00, rose to between 60 and 80 ppbv (a maximum of about 3 μmol m^{-3} or 300

Figure 1 Experimental set-up of indoor air biofilter. Air was drawn through four bioscrubbers (only two are shown) (a) by a dedicated air handling system (b) and returned it to the influent air mass(c). Fluxes were controlled with valves (d). To control influent, a peripheral computer (e) activated controlled air flow through one of four impingers of the specific VOC (f)(only one shown).

μg m^{-3}) at mid-night and back to 0 by 06:00. These influent concentrations were comparable to indoor levels (10). The four fluxes were applied separately to each biofilter on a diurnal basis (giving four replicates) at each of the three temperatures.

Estimation of Microbial Activity. The rate of VOC degradation is dependent on the partitioning of the VOC into the aqueous phase and the rate of microbial degradation. Either of these factors can be rate limiting and will be influenced by temperature differently. Calculated Henry's law constants for the

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three VOCs (11), clearly
indicate that, for a given
concentration of VOC
present in the air, the
amount partitioning into the
water varied considerably
over the range of
temperatures examined.
The rate constants (an
estimate of microbial
activity) were calculated for
· each biofilter at each
temperature based first order
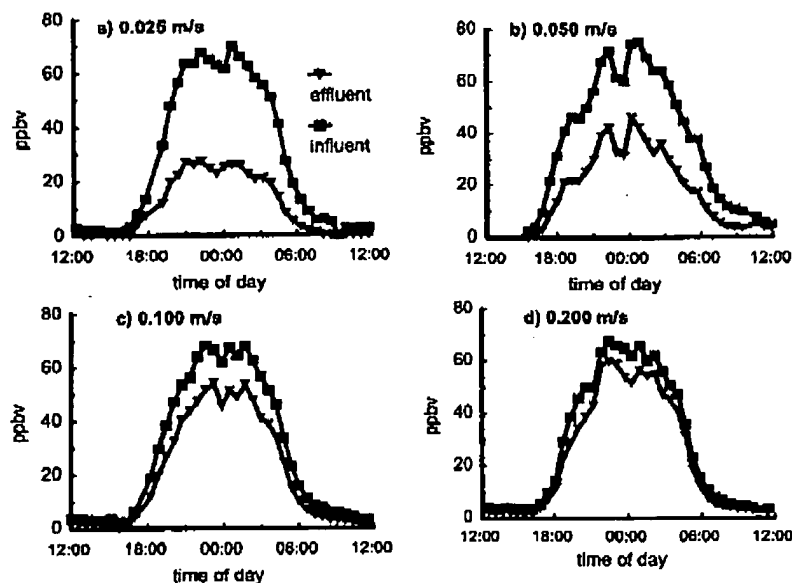kinetics (12) and subjected
to ANOVA.

Figure 2 The effluent and influent concentrations of
toluene passing through the bioscrubber

RESULTS AND DISCUSSION

Figure 2 indicates that the indoor biofilter can remove substantial amounts of toluene present in
very low concentrations. This was typical of TEX at all the different temperatures. Despite being
subjected to a relatively large range of concentrations, the effluent exhibited a good linear correlation
with the influent levels. Average r^2 for TEX over the range of temperatures and fluxes were
0.995±0.004, 0.994±0.005, and for 0.994±0.007, respectively.
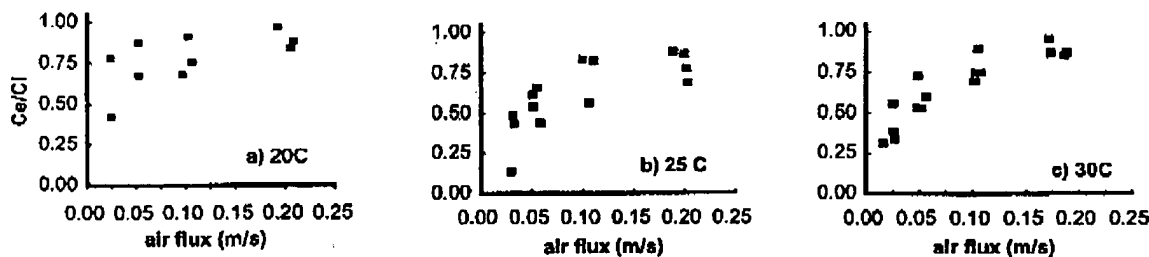

Figure 3 The ratio of effluent to influent (Ce/Ci) of toluene as a function of air flux
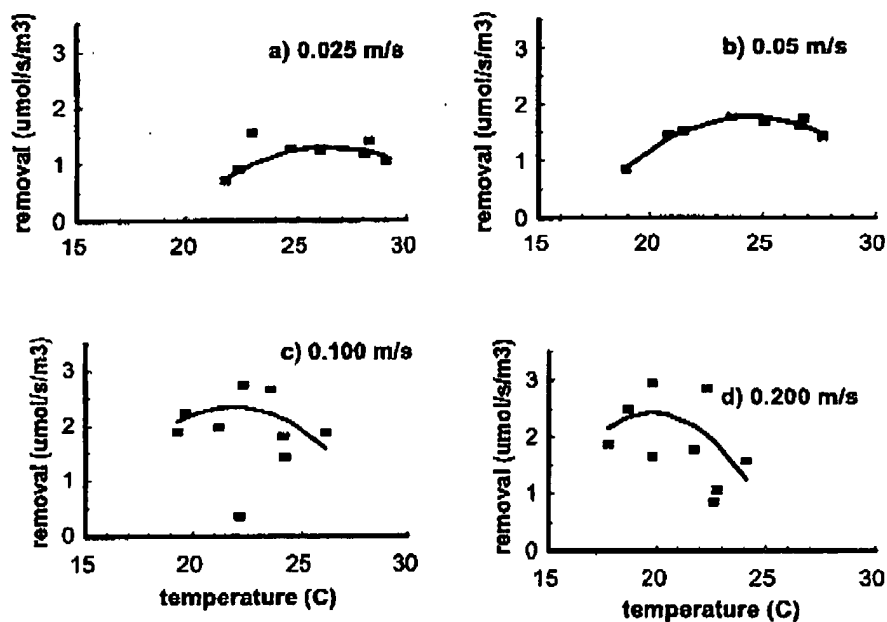through the bioscrubbers

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Figure 4 The elimination capacity of o-xylene over a range of temperatures and air fluxes.
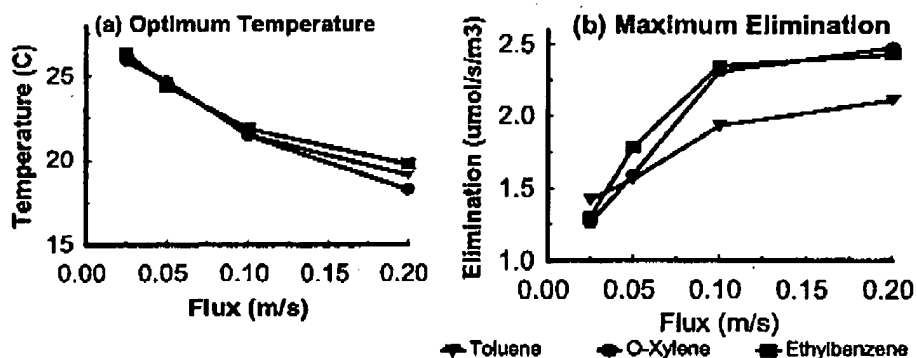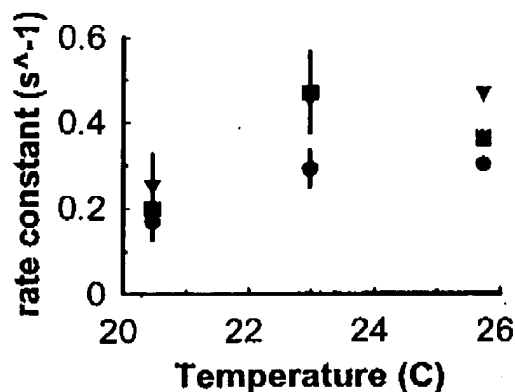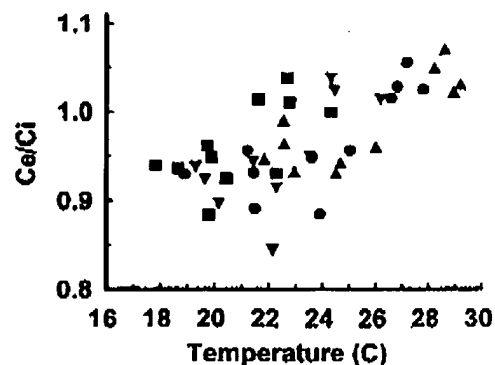

Figure 5 The (a) optimal temperature of operation and its corresponding (b) maximum removal rates by the biofilters subjected to TEX influent concentrations of 1.5 μmol m$^3_{air}$. The values were calculated from the polynomial lines of best fit presented as in Figures 4.

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Figure 6. Microbial rate constants for TEX over a range of temperatures.

Figure 7. The effluent to influent ratios (Ce/Ci) for PCE over a range of temperatures and fluxes.

The ratio of effluent to influent over the range of fluxes and operating temperatures for toluene are presented in Figure 3. All three compounds exhibited similar decreasing removal efficiencies (1-the ratio of effluent to influent) with increasing flux at all temperatures. This is consistent with other biofilters loaded with much higher levels of VOCs (13, 14). The elimination capacity of the biofilters subjected to a theoretical influent concentration of 1.5 μmol m^{-3}_{air} (the mid point of the applied range) was plotted as functions of effluent temperature and air flux in Figure 4. At the slowest flux, a definite optimum temperature was apparent and, as the flux increased there was a shift to a lower optimum temperature. Optimum temperatures and maximal elimination capacity for each VOC across the range of fluxes (based upon the second derivative of calculated polynomial models) were determined and are presented for toluene in Figure 5. The behaviour across the range of fluxes was very similar for all TEX. For all three, maximum elimination occurred at the most rapid fluxes, with relatively small differences between the elimination at 0.100 and 0.200 m s^{-1} (between 5% and 10% greater removals at the more rapid flux). The TEX elimination rates correspond to removal of roughly 0.5 g_{voc} $m^{-3}_{biofilter}$ h^{-1} at the slowest flux and 1.0 g_{voc} $m^{-3}_{biofilter}$ h^{-1} at the most rapid flux. Although these values are low compared to industrial biofilters (14) it still represents substantial removal. Figure 5 clearly indicates that the enhanced removal under the rapid influent fluxes was associated with a reduction in the optimum operating temperature. Although industrial biofilters for styrene reported optimum removal within the range reported here (15), optimum temperatures for most BTEX biofilters were 30°C (16) or higher (14).

The microbial rate constants (s^{-1}) were subjected to ANOVA. Further analysis indicated all biofilters had similar responses to temperature for each VOC. The results are presented in Figure 6. For all three VOCs, there was a significant reduction in the microbial rate constant at the cooler operating
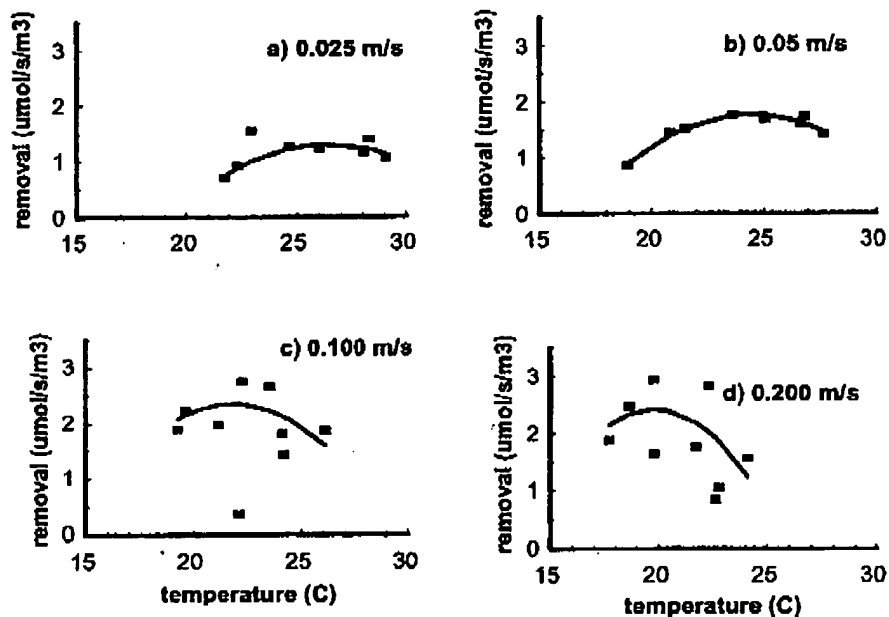
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Figure 4 The elimination capacity of o-xylene over a range of temperatures and air fluxes.
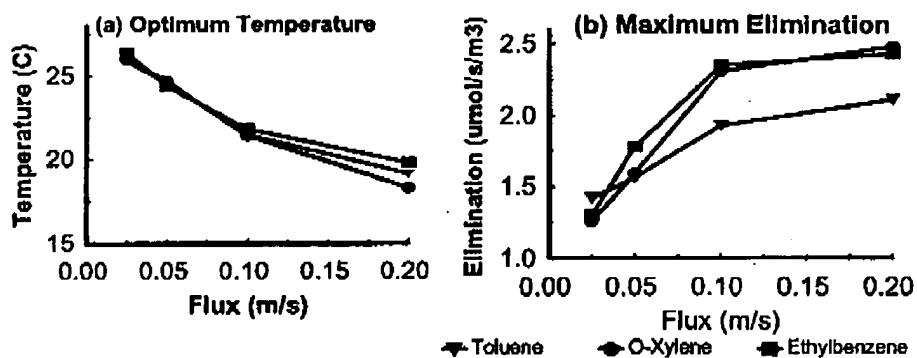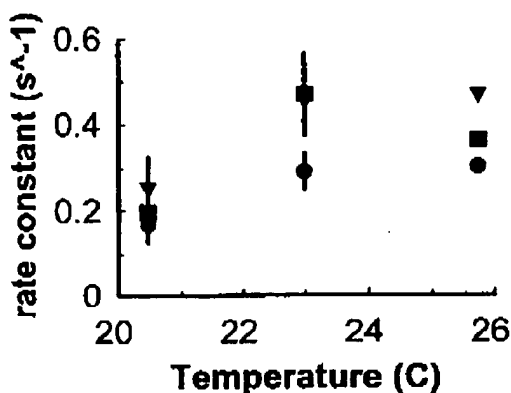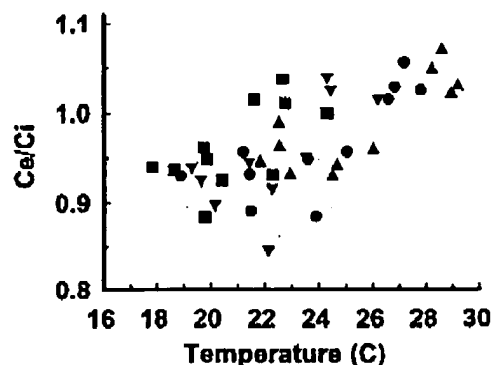

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temperature (20°C) with no significant difference between 23 and 26°C. Examining the influence of temperatures between 15 and 50°C on industrial trickle bed biofilter, Lu and coworkers (16) found the rate constant dropped quickly below 25°C. Significant microbial population shifts have been reported at 23° (15) and 30°C (16). It is interesting to note that, as in earlier studies (7, 8), there was no acclimation period associated with change in flux. However, temperature changes required up to 4 days of acclimation. This supports the notion of changes in the degrader populations.

Unlike TEX, the biofilter could removed limited amounts of the chlorinated compound PCE. The removal of chlorinated VOCs was largely governed by the temperature of the biofilter temperature (Figure 7). Maximum removal occurred at the coolest operating temperature. Under the warmer water temperatures, effluent levels were frequently higher than influent levels, suggesting the heated water was off gassing PCE into the effluent. This suggested that the system can remove the chlorinated VOCs from the air but once sorbed into the water column, was unable to degrade the material quickly enough to have any impact on air quality. This persistence of PCE supports our earlier observation of the accumulation of chlorinated VOCs in the aquatic component of the biofilter (8).

CONCLUSIONS

Although the presented work was not designed to test the effectiveness of this biofilter relative to other systems, several observations can be made about the performance of a biofilter subject to very low influent concentrations. First, although chlorinated materials may be problematic, these results indicate that biofiltration can remove VOCs present at concentrations typical of the indoor environment. Thus, the use of biofiltration to replace or supplement traditional ventilation techniques to maintain indoor air quality deserves further consideration. The effective removal of certain VOCs through a relatively thin biofilter could, in part, be due to the use of living plants as a biofilter packing medium. Biofilters subjected to these low VOC concentrations respond in a manner similar to industrial biofilters. However, the system is not limited by microbial activity (potentially a consequence of the use of living botanical as a filter medium) but rather is substrate limited. Thus the filter removes TEX most effectively at low temperatures.

Operating the indoor air biofilter at cooler temperatures has benefits on indoor air quality beyond improved VOC removal. If the biofilter is maintained several degrees cooler than the indoor space then as the cooler water-saturated air exits the biofilter, it will be warmed and dried by the ambient air mass. This will reduce the negative impact of the water vapour on the indoor environment. Maintaining the biofilter at cool temperatures also limits the probability of the pathogen Legionella.

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